Recent results with the XENONnT experiment

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on behalf of the
XENONnT Collaboration
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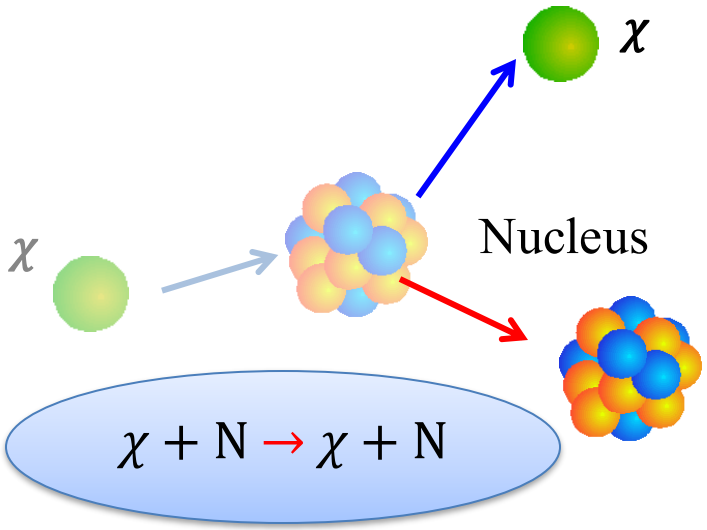
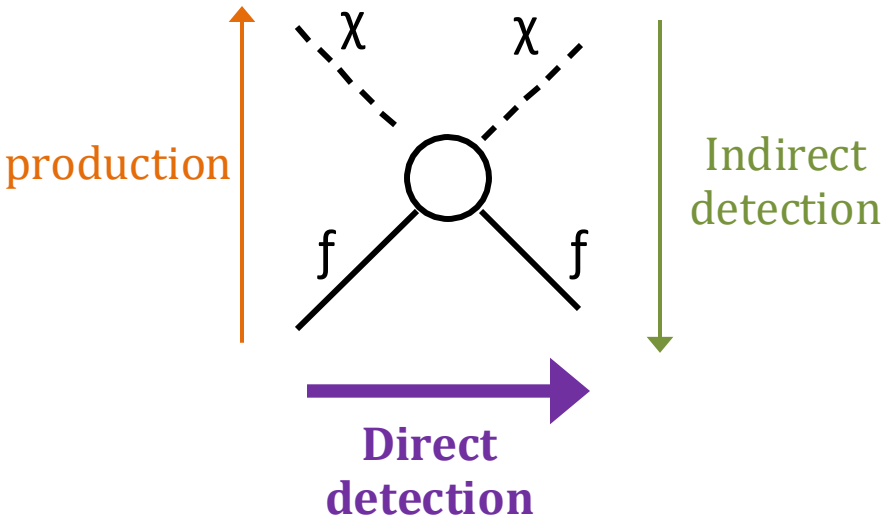
WIMP direct detection principle

Nuclear Recoil (NR)



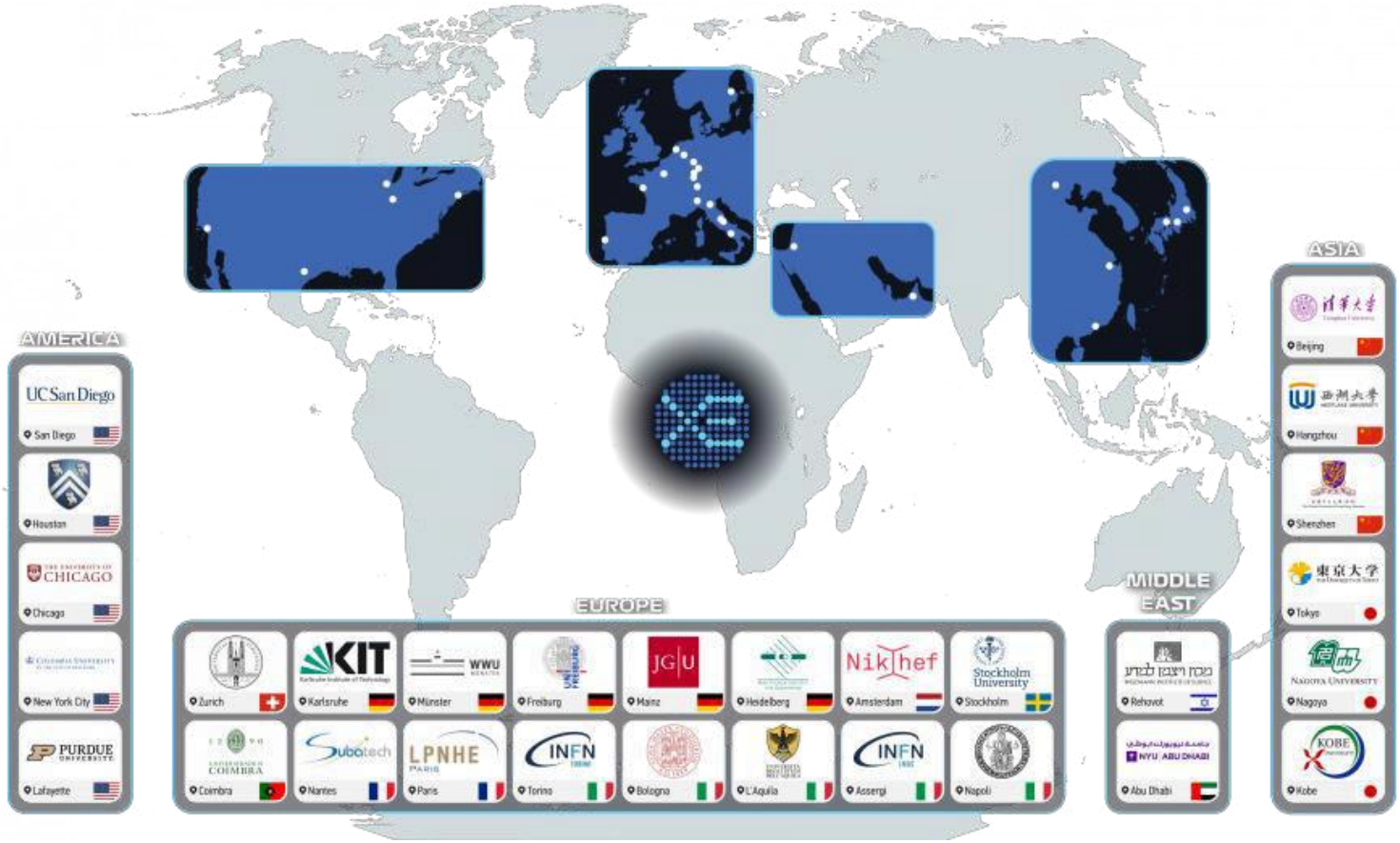
Recoil energy
~1-100 keV



Electronic Recoil (ER)

γ and β particles interact with the atomic electrons
➔ Background in « standard WIMP analysis »

XENON Collaboration



200 + scientists

29 institutions

12 countries

New results

Main Motivation

Discover Weakly Interacting Massive Particles (WIMPs).

arXiv:2502.18005 [hep-ex]

Other recent studies

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS), $0\nu\beta\beta$, Solar Axions and ALPs, Supernovae, etc.

Phys. Rev. Lett. 133, 191002

XENON timeline

XENON10

XENON100

XENON1T

XENONnT

2005 2009 2016 2020

Target Mass

15 kg

161 kg

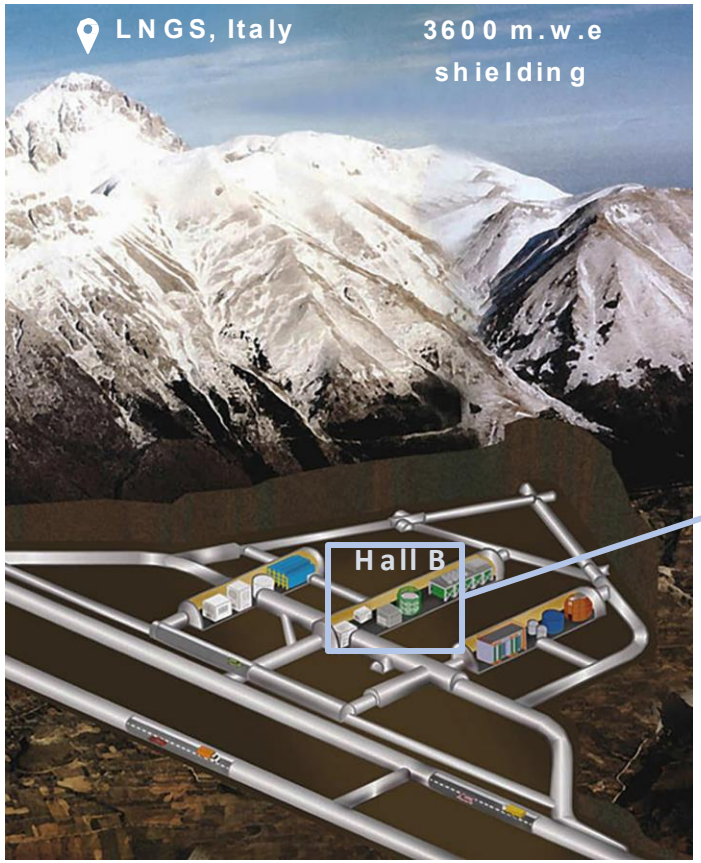
3.2 t

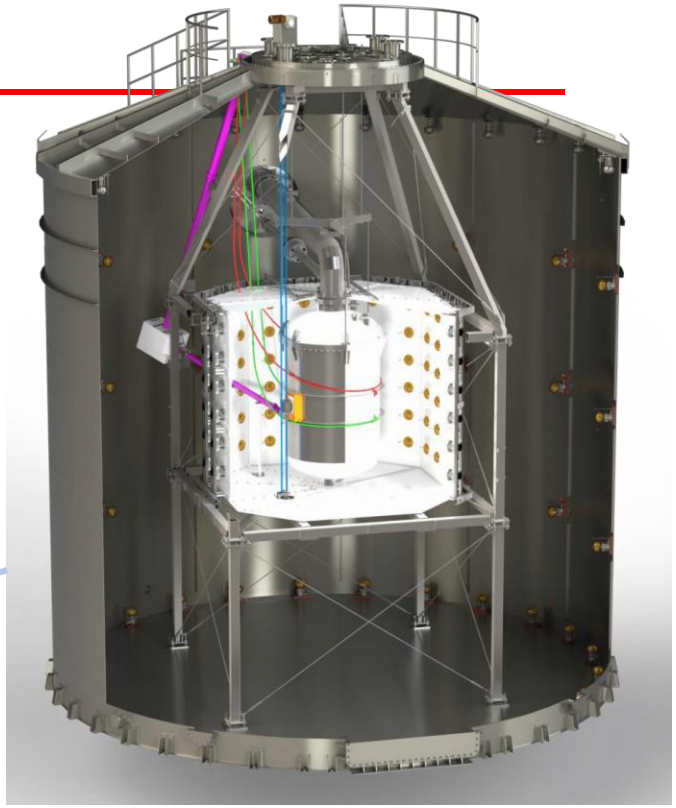
8.6 t

Relative background

1	$5 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	$3 \cdot 10^{-5}$

XENONnT Experiment





3 Nested Detectors

Sharing the same DAQ

➢ **LXe Dual Phase Time Projection Chamber (TPC)** with 5.9t active volume.

(Eur. Phys. J. C 84, 784 (2024), JCAP11(2020)031)

➢ Gd-doped Water Cherenkov **Neutron Veto (NV).**

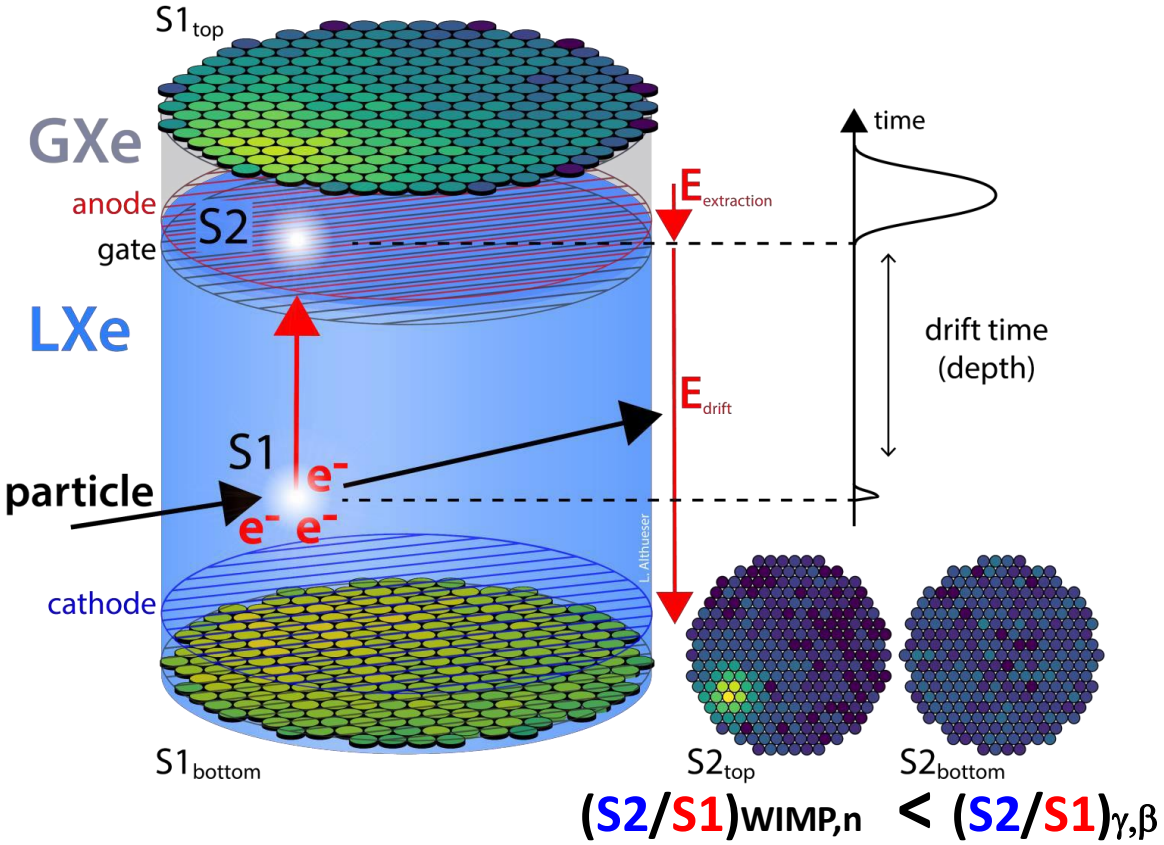
(arxiv:2412.05264)

➢ Gd-doped Water Cherenkov **Muon Veto (MV)**

(2014 JINST 9 P11006)

Dual phase TPC: principle

TPC = Time Projection Chamber



$(S2/S1)_{WIMP,n} < (S2/S1)_{\gamma,\beta}$

S1:

→ Photon (λ = 178 nm) from Scintillation process

S2:

→ Electrons drift

→ Extraction in gaseous phase

→ Proportional scintillation light

3D reconstruction :

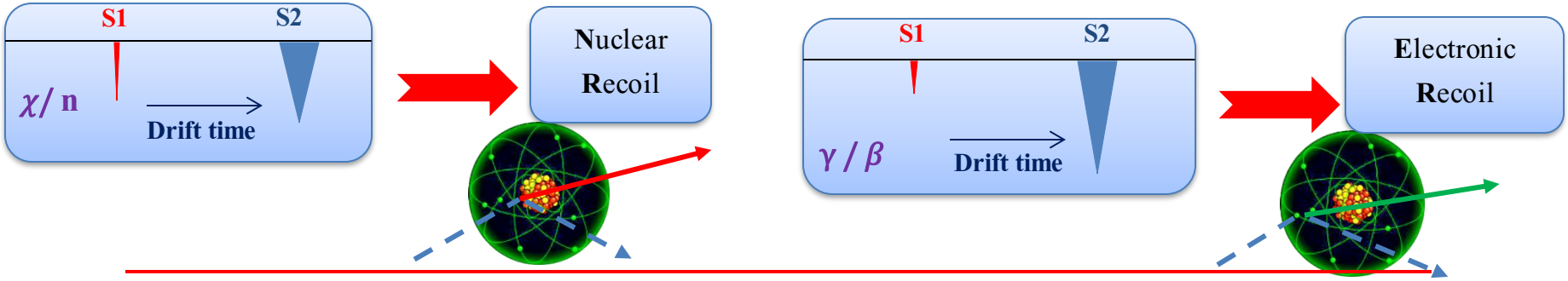
→ X,Y from top array

→ Z from Drift time

Energy reconstruction :

→ S1 & S2 area combined

→ Calibration of known sources



XENONnT Infrastructure

Rn Distillation

- Continuous online distillation.
- ^{222}Rn conc (SR0): $1.9\ \mu Bq/kg$
- ^{222}Rn conc (SR1): $0.9\ \mu Bq/kg$

Eur. Phys. J. C (2022) 82: 1104

arXiv:2502.04209

Kr Distillation

- ^{nat}Kr/Xe concentration **< 50 ppq**

Eur. Phys. J. C 77, 275 (2017)

nT DAQ

- **Triggerless** DAQ. Shared between three detectors. 2023 JINST 18 P07054

LXe Purification

- Removes **electronegative** impurities. Eur. Phys. J. C (2022) 82: 860

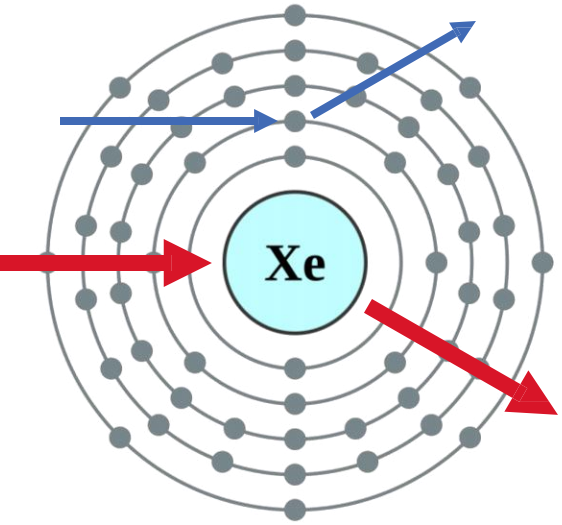
ReStoX 1 & 2

- **Recovery and Storage for Xenon** GXe/ LXe / SXe

arXiv:2402.10446

Recoil Type Discrimination: ER or NR?

Electronic Recoils (ER)

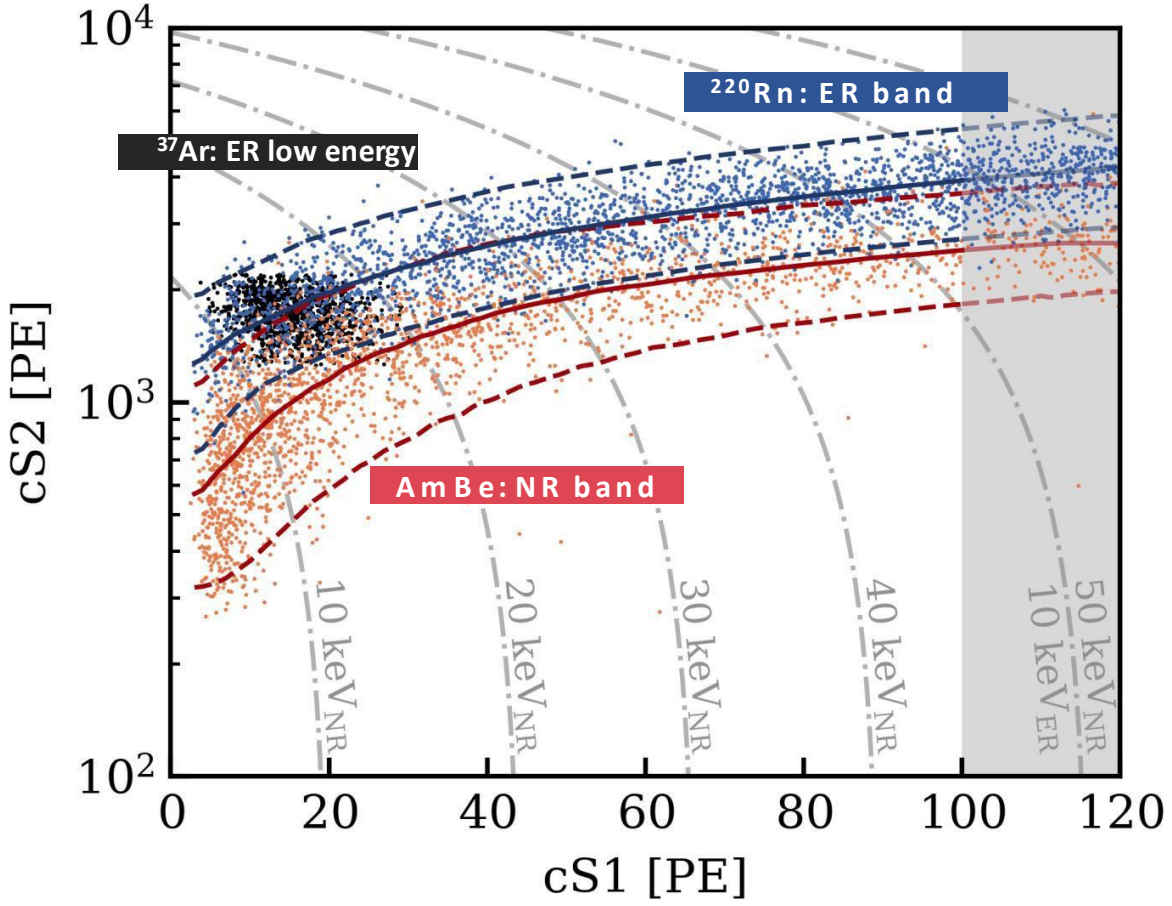


Nuclear Recoils (NR)

NR
- ✗ | Neutrons
- ✓/✗ | Neutrinos (CEvNS)
- ✓ | WIMPs

ER
- ✗ | Gamma & Beta
- ✓/✗ | ^{136}Xe $0\nu\beta\beta$, $2\nu\beta\beta$.
- ✓/✗ | Neutrino elastic scattering.
- ✓ | Solar axions, ALPs.

✓ Signal ✗ Background



^{83m}Kr

TPC characterization and signal correction.

^{232}Th

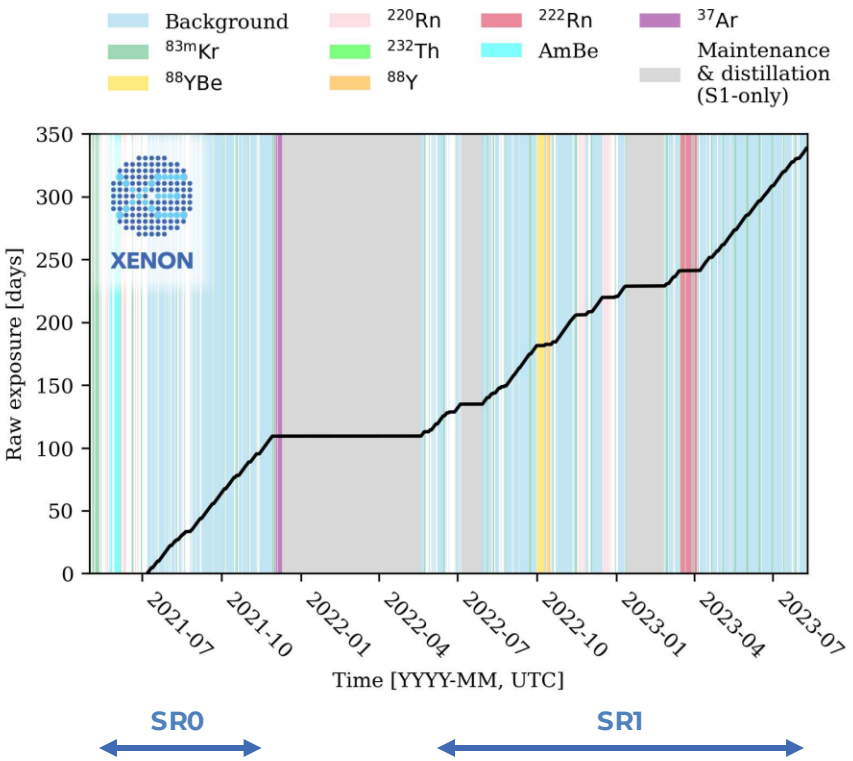
High energy Response.

YBe

Low energy NR response specially tuned for the CEvNS search.

arXiv: 2412.10451

Science Data



Full SR0 + SR1 dataset :
- WIMP search
- CEvNS search

SR0 **95.1 days**
- Updated neutron background model with new MC
- Other models remain unchanged

SR1a **66.6 days**
- Radon removal system in high-flow mode
  -> 1μBq/kg ^{222}Rn activity
- A small amount of dirty xenon injected
  -> high ^{85}Kr, ^{37}Ar, ^{3}H-like background
- Includes a short period of distillation system running

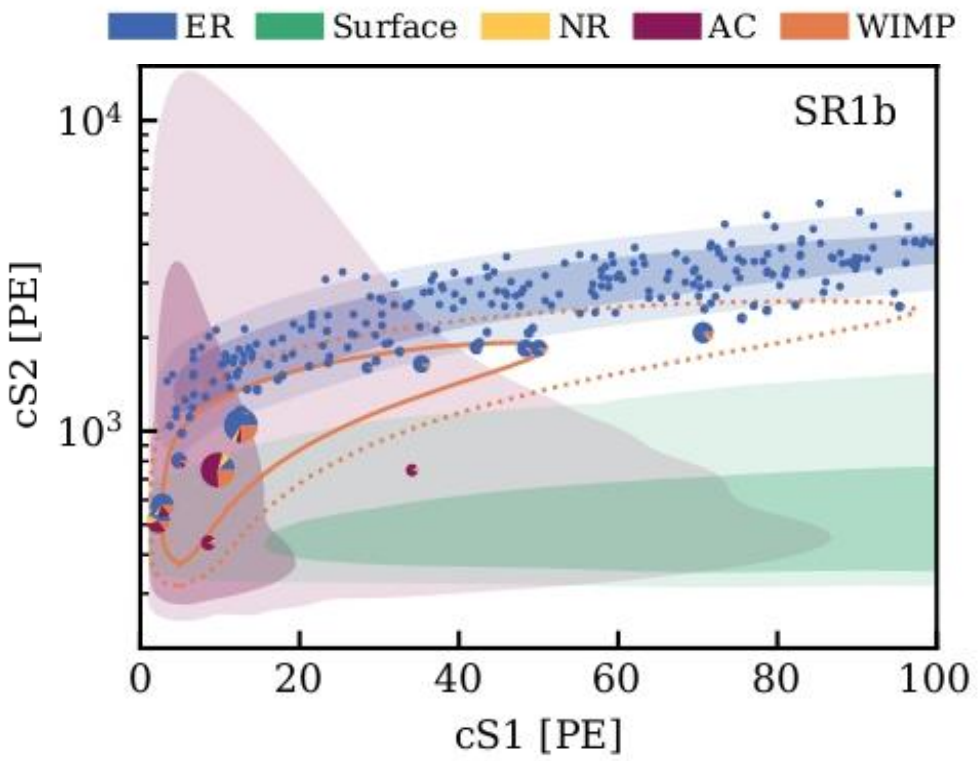
SR1b **119.9 days**
- Radon removal system in high-flow mode
- ^{85}Kr, ^{37}Ar back to SR0 level, ^{3}H-like background still remained

SR0+SR1 **281.6 days**

- Very stable detector conditions. <1%(<3%) variation in Light (Charge) Yield.
- **High liquid xenon purity**: electron lifetime ~20ms.

Backgrounds

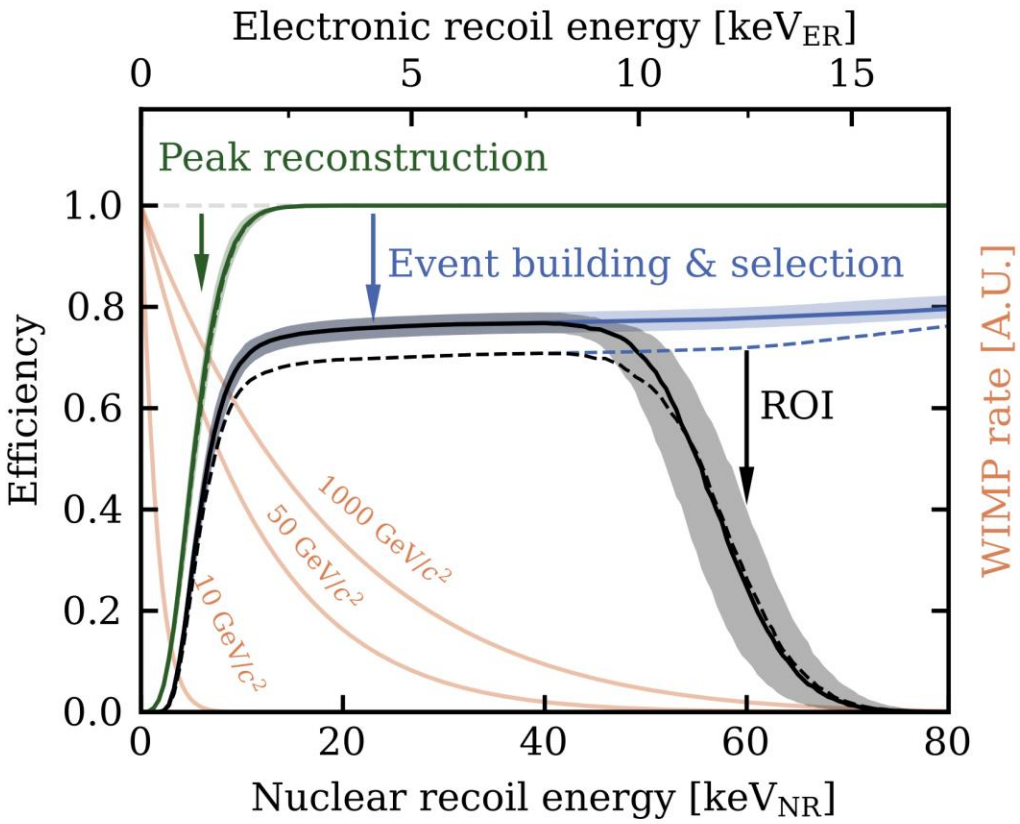
arXiv:2502.18005 [hep-ex]



- Electronic Recoil (ER)
  constrained by calibration & spectrum fitting
- Accidental Coincidences (AC): random pairing of S1 and S2 signals
  constrained by BDT cuts based on shape and spatial information of S2 peaks.
- Surface/Wall: plate-out on the PTFE wall of the TPC
  constrained by choice of FV
- Nuclear Recoil backgrounds:
  o CEvNS
  (constrained by solar neutrino flux / uncertainty driven by NR model).
  o Neutrons
  (reduced by veto tagging / constrained by the sideband unblinding)

Efficiency

arXiv:2502.18005 [hep-ex]



- **Peak reconstruction efficiency** dominated by 3-fold requirement (3 PMTs to be in coincidence)
- **Event building efficiency** is dependent on the clean ambience requirement of an event

  e.g. higher background rate
  -> higher rate of photoionization peaks and delayed electrons
  -> lower event building eff"
  (arxiv:2409.08778 – SR0 analysis paper)

- **Selection**: S1/S2 consistent with signal-like, S2 consistent with e-diffusion, quality cuts and fiducial volume.
- **ROI**: cS1 < 100 PE
  cS2 [$10^{2.1}$ PE, $10^{4.1}$ PE]

Fit to unblinded data

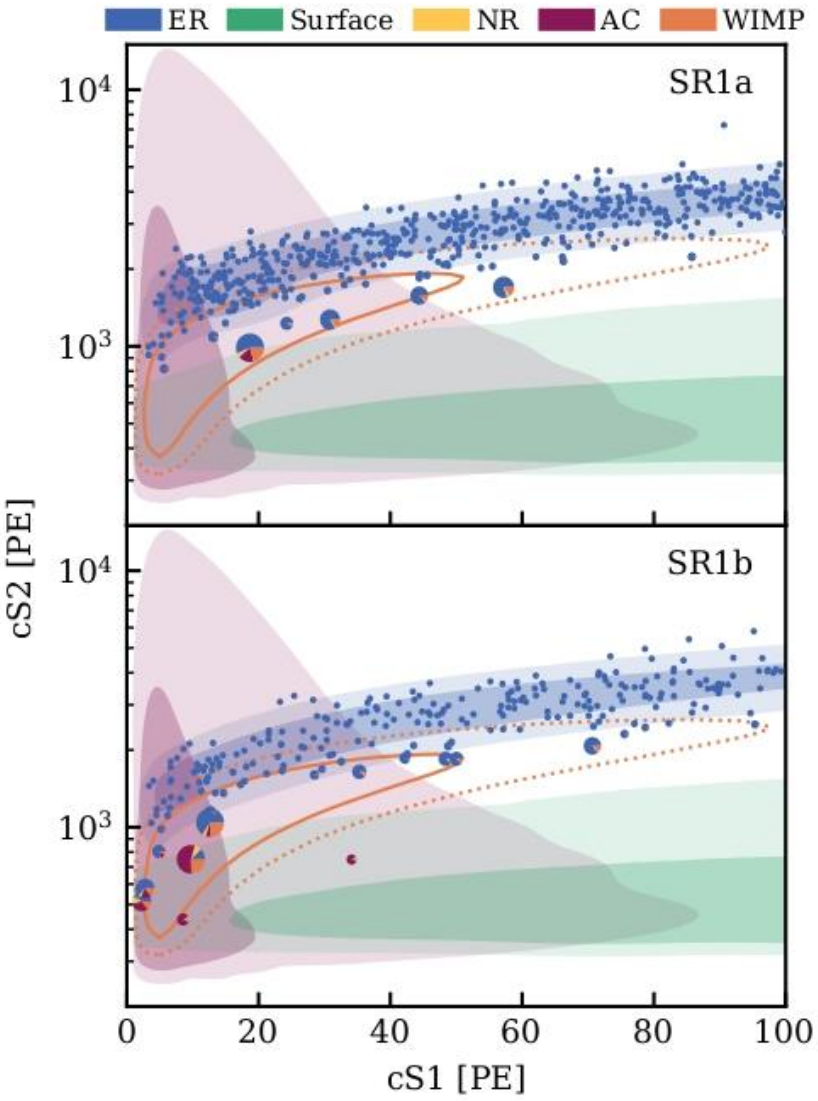
arXiv:2502.18005 [hep-ex]

- Total exposure: **3.1 t.y, 3-fold analysis.**

- SR1 likelihood divided into two:
  - **SR1a:** 1/3rd of exposure, high ER bg rate.
  - **SR1b**: 2/3rd of exposure, lower ER bg rate.

- SR1 unblinding in two steps:
  - Small region above NR median and $E > 5keV_{ER}$ unblinded to **identify any ER leakage & test the DEC yield model**
  - Followed by full unblinding.

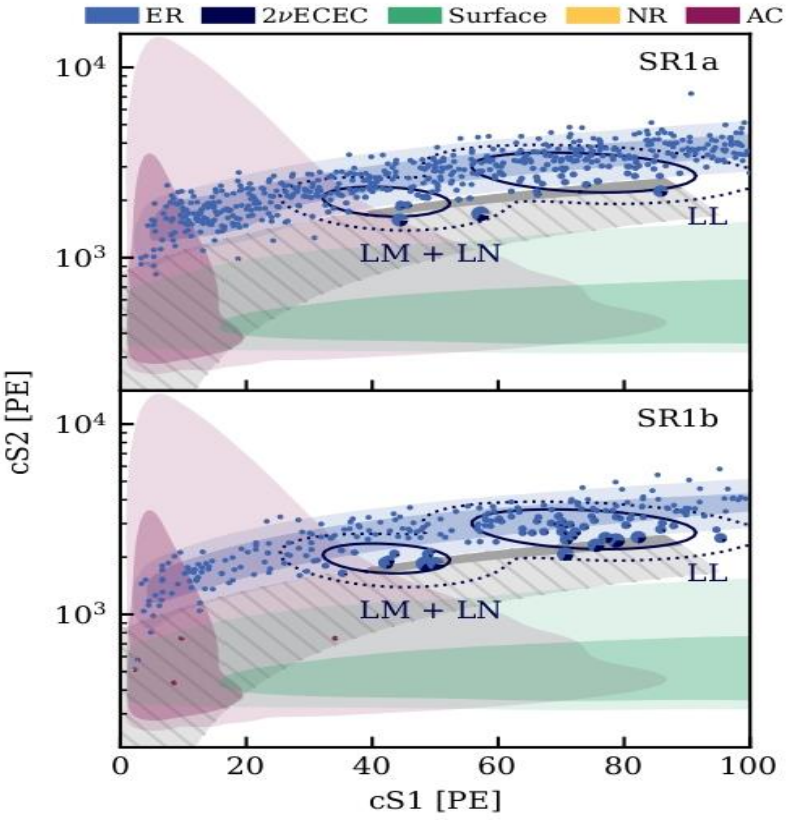
No excess over background is observed.



Charge yield of ^{124}Xe DEC

arXiv:2502.18005 [hep-ex]

- Suppressed charge yield for ^{125}Xe L-shell EC (~0.9Q_β) reported by XELDA (Phys. Rev. D 104, 112001).
- No measurements available at nT drift field.
- **^{124}Xe DEC** LL (~10keV) and LM+LN (~6keV) inside WIMP RoI.
- ^{124}Xe DEC expected event rate in nT exposure: (4.5 ± 0.7) in SR0 and (9.1 ± 1.4) in SR1.
- Adding CY-suppression as nuisance parameter can absorbing leakage from other ER; **artificially lowering the limits.**
- First perform PLR test nominal model against model with unconstrained CY on SR1 data. Test size pre-defined to limit false WIMP discovery rate.
- No rejection of the nominal model!



Best fit:

$$Q_{LL} = \mathbf{0.8^{+0.08}_{-0.04}}\, Q_\beta \;,\; Q_{LM} = \mathbf{0.72^{+0.11}_{-0.04}}\, Q_\beta$$

SR0+1: WIMP Search

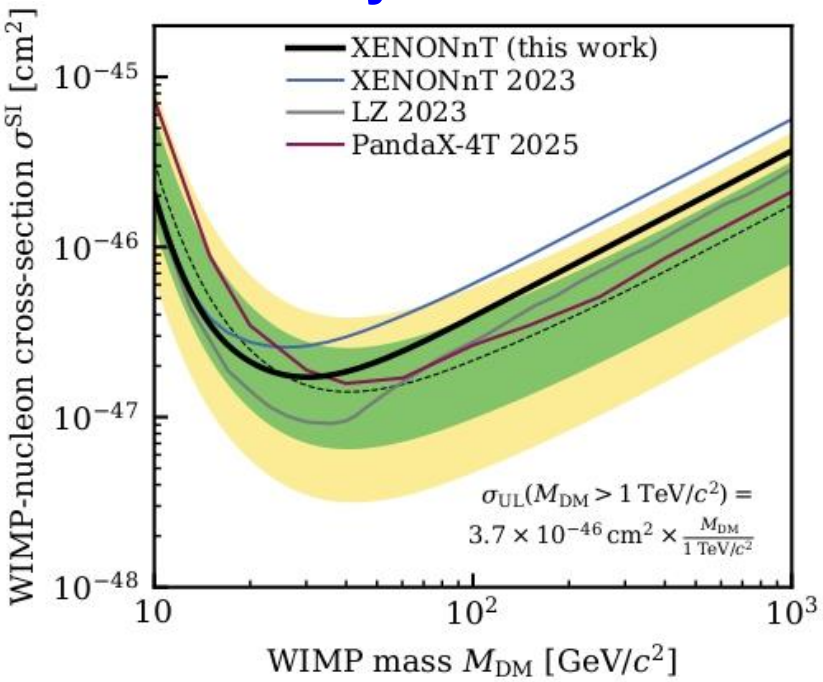
arXiv:2502.18005 [hep-ex]

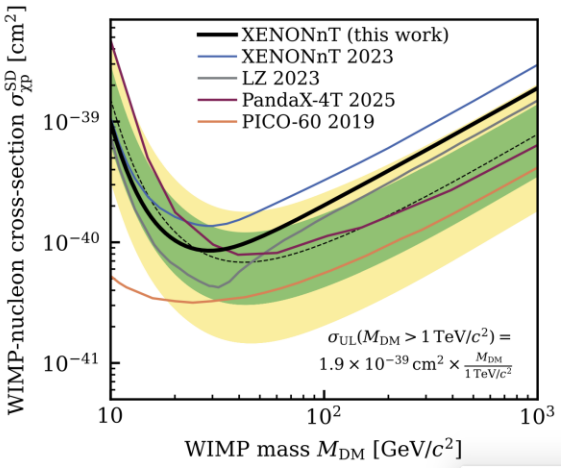
Blinded Analysis

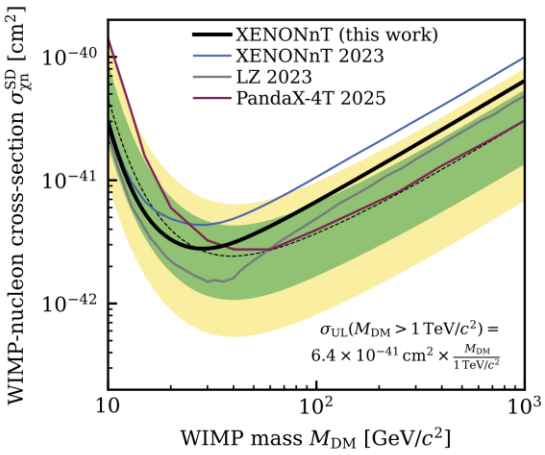
New **limits** set on WIMP-nucleon cross section. Improvement from SR0 by a factor of **~1.5**

Best limit at WIMP mass of $\mathbf{30\ GeV/c^2}$.

The results are consistent with other experiments

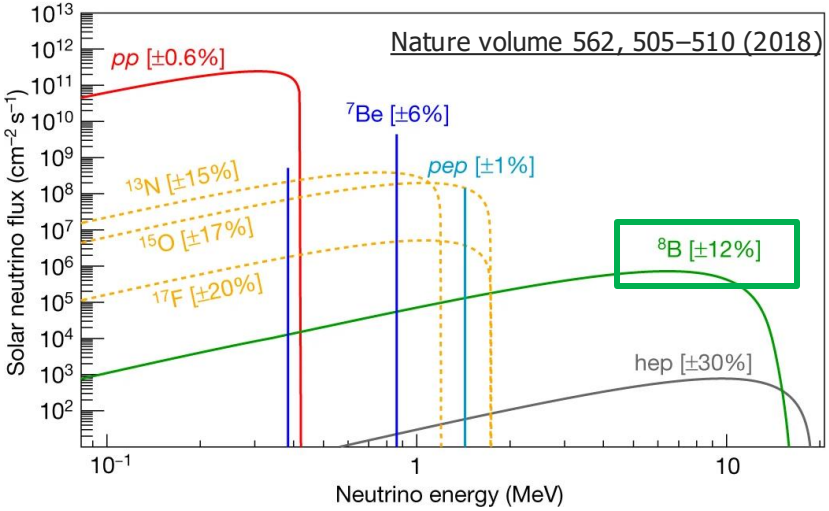




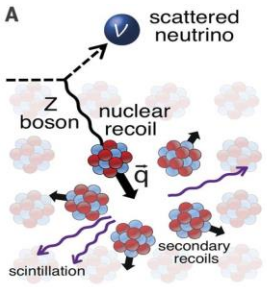


CEvNS Search

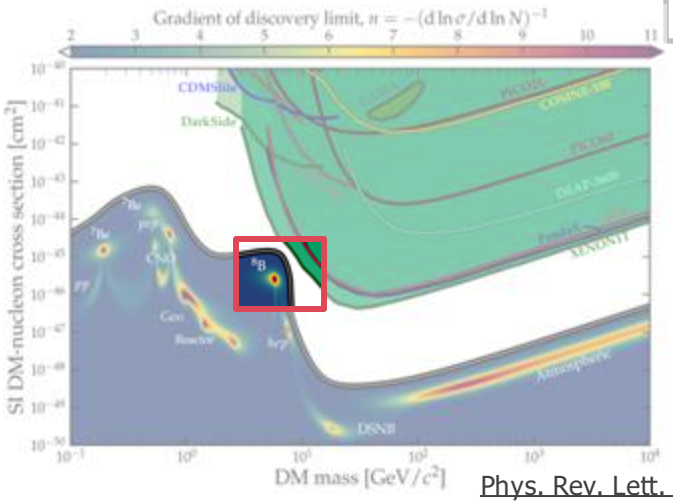
- **CEvNS: C**oherent **E**lastic **Neutrino-N**ucleus **S**cattering; allowed by SM.
- First predicted in **1974** (Phys. Rev. D 9, 1389). First observed by COHERENT in **2017** (D. Akimov et al, Science 357 (2017)).
- **Previously, never measured** with a Xenon target or with neutrinos from astrophysical sources.



Solar neutrinos from ^{8}B is expected to have the highest number of detectable signals in XENONnT.



D. Akimov et al, Science 357 (2017)



Phys. Rev. Lett. 127, 251802

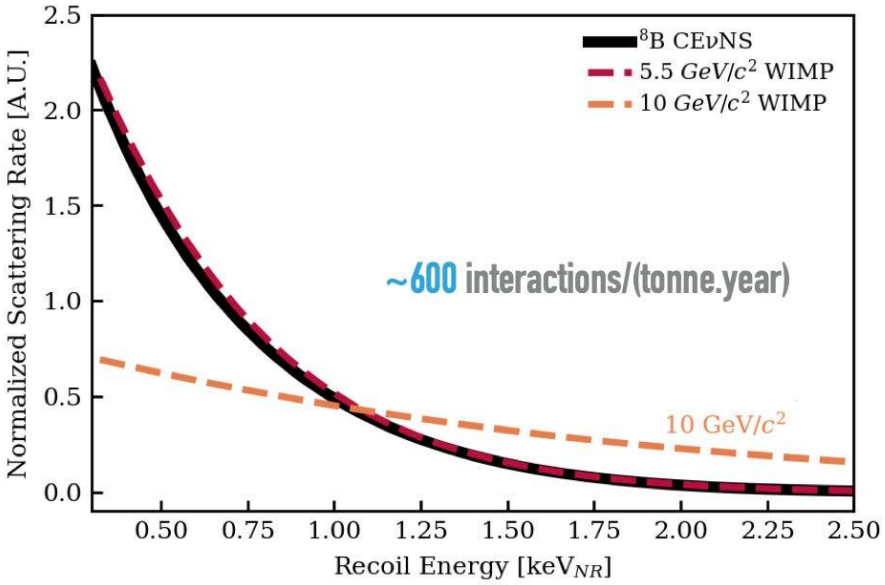
Dedicated analysis (lower thrershold)
Observed ^{8}B CEvNS
at a significance of 2.73σ.

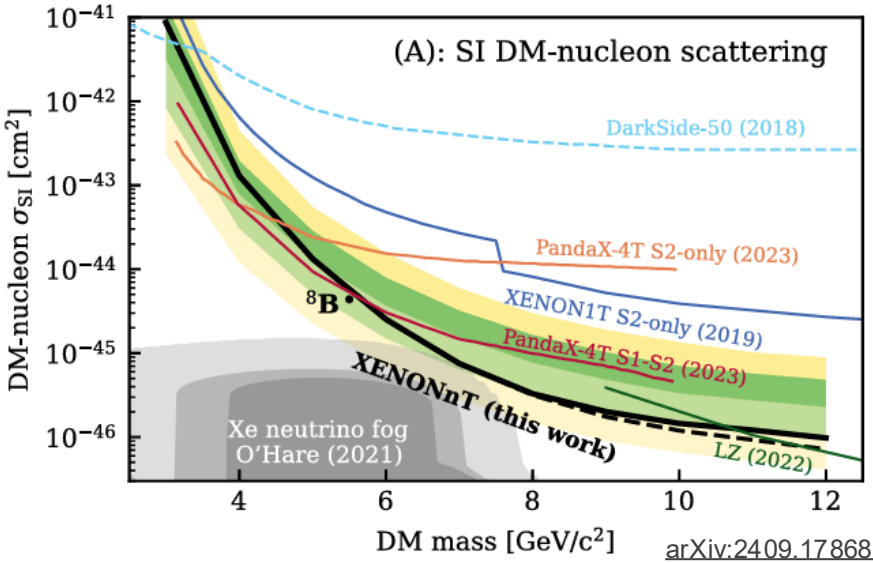
^{8}B CEvNS: Nearly **indistinguishable** from a 5.5GeV WIMP.

Entering the **neutrino fog**

Low Mass DM Search

CEvNS is a background for DM search

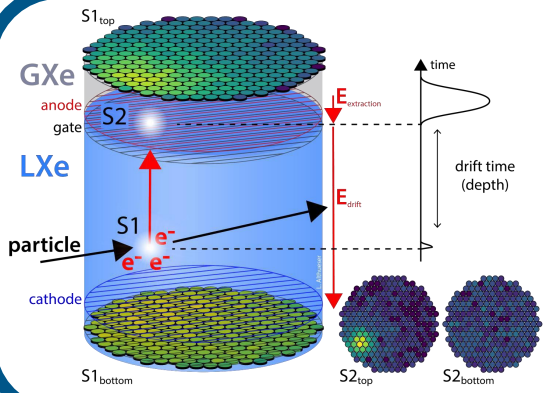




- Same dataset and analysis framework for CEvNS search is used.
- Here, **^{8}B CEvNS becomes a background**.
- **No excess** over background observed.
  - New parameter space excluded.
  - First search into the neutrino fog.

arXiv:2409.17868 [hep-ex]

Conclusions



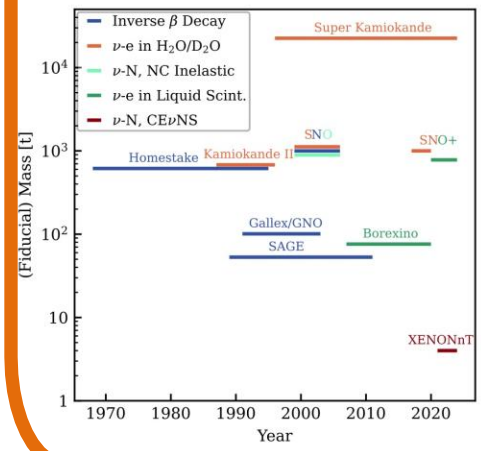
XENONnT experiment:

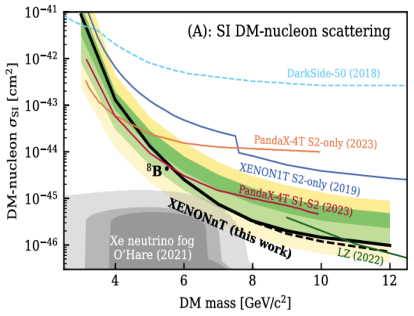
TPC with 5.9t active LXe target

Data taking & analysis ongoing

Xenon-**L**ux **Z**eplin-**D**arwin collaboration established to build the **next gen-LXe TPC** with upto 60t target mass.

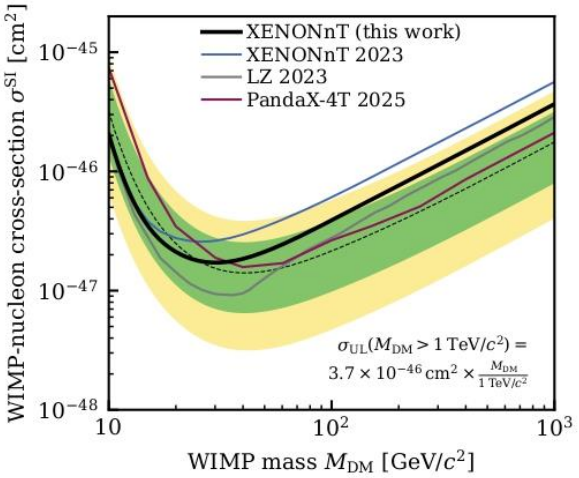
Observed ^{8}B CEvNS at a significance of $\mathbf{2.73\sigma}$.





Low mass WIMPs search

SI WIMP search ("standard" 3-fold)



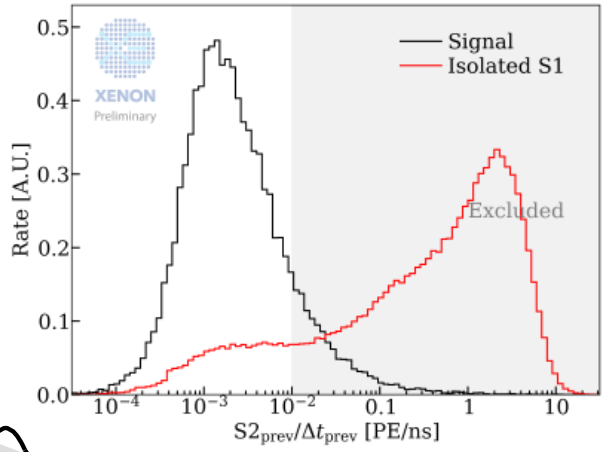
No excess observed in a blind analysis.

Best limit: $\mathbf{1.7 \times 10^{-47} cm^2}$

$(m_{WIMP} = 30\, GeV/c^2)$

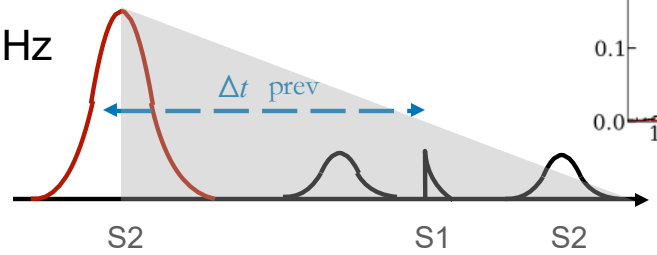
CEvNS – Background Model

Accidental Coincidences Suppression:



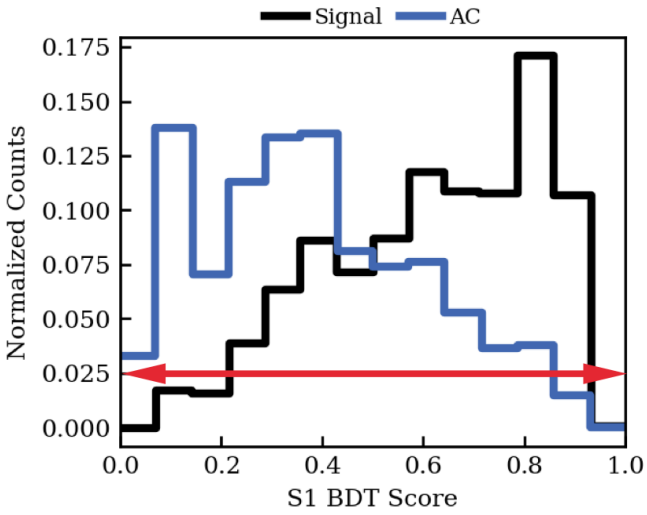
1- Time Shadow

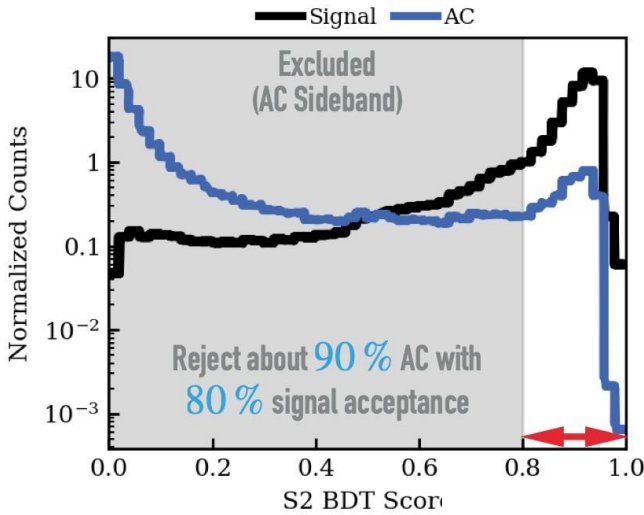
- Use space/time correlation with previous high-energy interaction
  - ➢ Isolated S1 rate: 15 Hz → 2.3 Hz
  - ➢ Isolated S2 rate: 150 mHz → 25 mHz



2- Two Boosted Decision Tree (BDT)

- S1 BDT: leverage S1 pulse shape and spatial distribution across the PMT arrays.
- S2 BDT: check that S2 pulse shape correlated with the diffusion of the drifting electron cloud law.

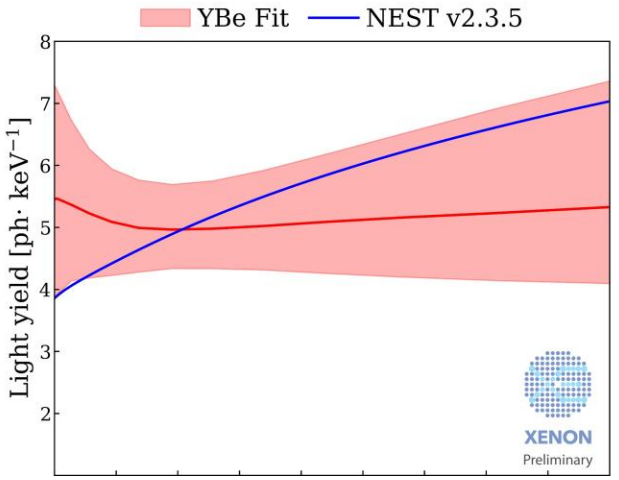


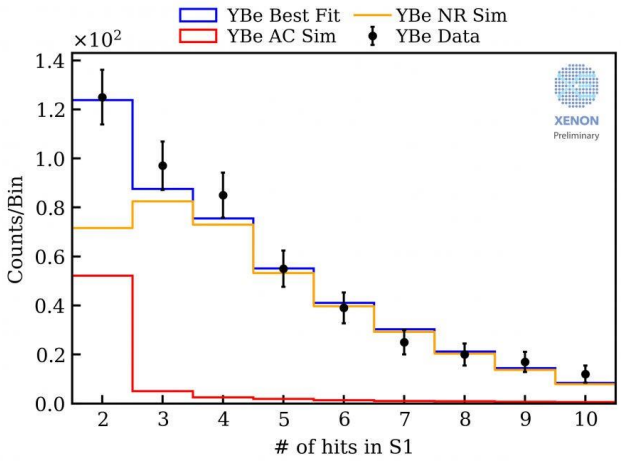


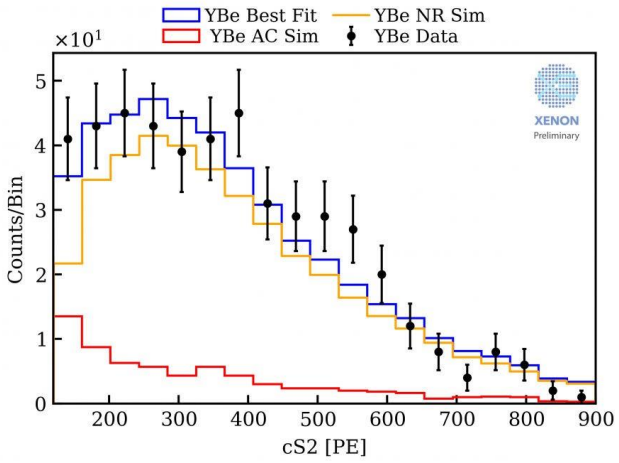
CEvNS – Yields model from ^{88}YBe Calibration

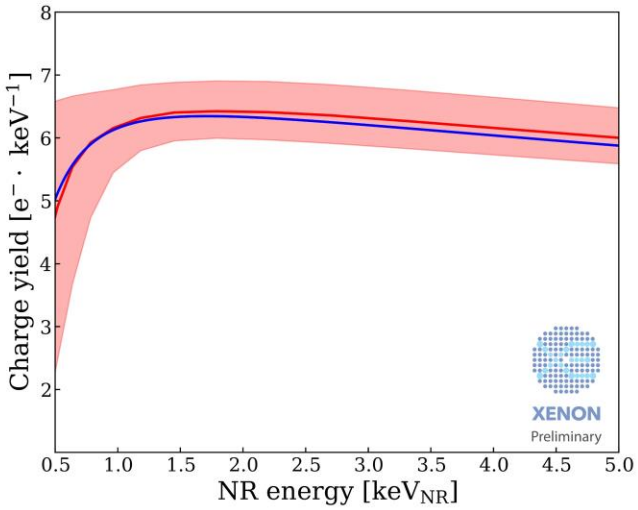
Constrain Yield Models: $\gamma(^{88}\mathrm{Y}) + ^{9}\mathrm{Be} \rightarrow n + ^{8}\mathrm{Be}$

- Great agreement between data and model.
  - ➢ Background originating from Accidental Coincidences (AC) are modelled with data-driven simulation framework.
- Light (LY) and Charge Yields (CY) were extracted down to 0.5 keVNR at XENONnT electric field of 23 V/cm with latest NEST parametrisation.
  - ➢ Yield model uncertainty leads to ~ 30% signal rate uncertainty.









CEvNS Search – Signal Region of Interest

Phys. Rev. Lett. 133, 191002

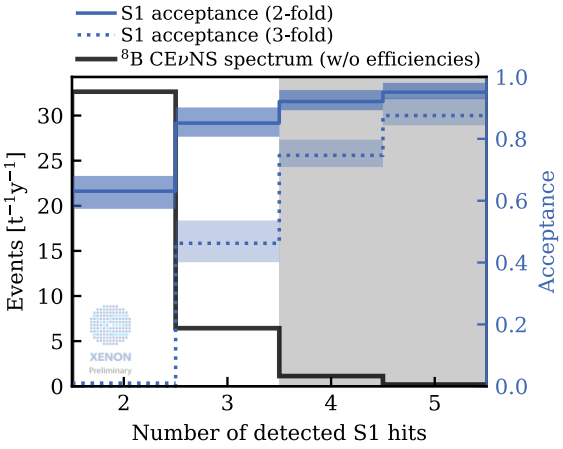
Boost sensitivity by lowering our energy threshold

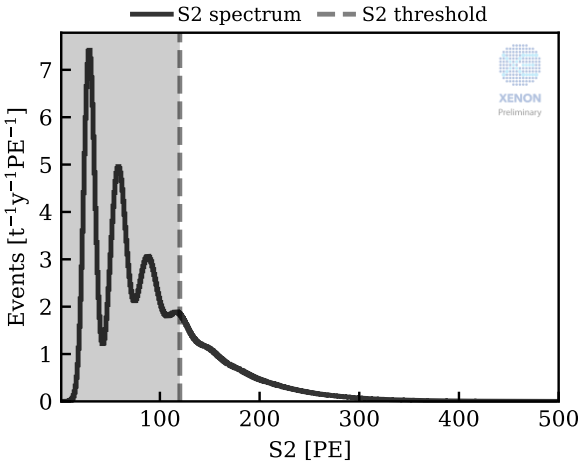
- ^{8}B event rate in the conventional WIMP “3-fold analysis" (SR0): ~1% detection efficiency → 0.2 events / (t x yr)
- Lowering our S1 and S2 threshold → improve our expected event rate to 3.7(3.3) events / (t x yr) in SR0(1)

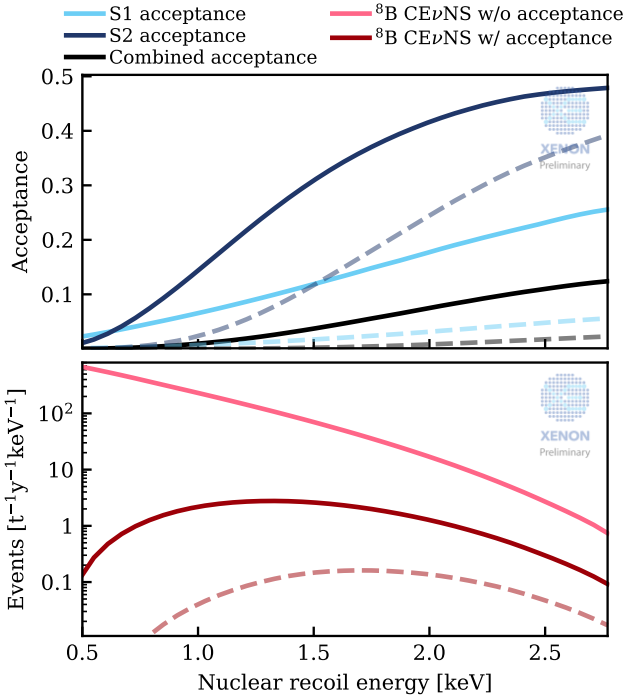
Blinded Region of Interest

S1 ROI: 2 or 3 hits ; A hit corresponds to a recorded photon by PMT+DAQ+software

S2 ROI: [120 - 500] PE → Reject high rate of isolated S2 background signal







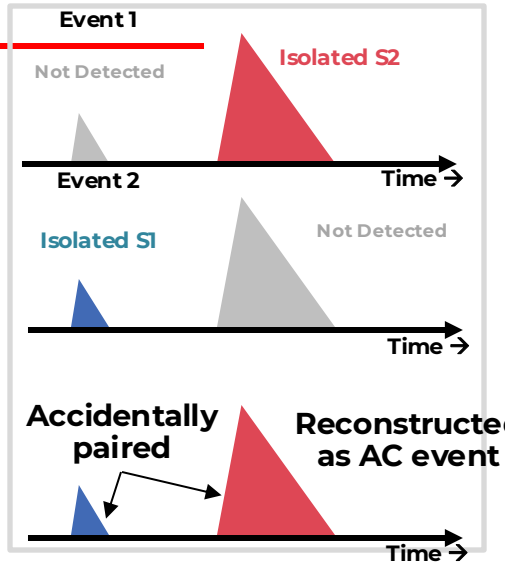
CEvNS Search – Prediction

Main Source of background: Accidental Coincidences

Accidental Coincidence (AC): Random pairing of **isolated S1** and **isolated S2**, whose exact origin is under investigation. Current culprit:

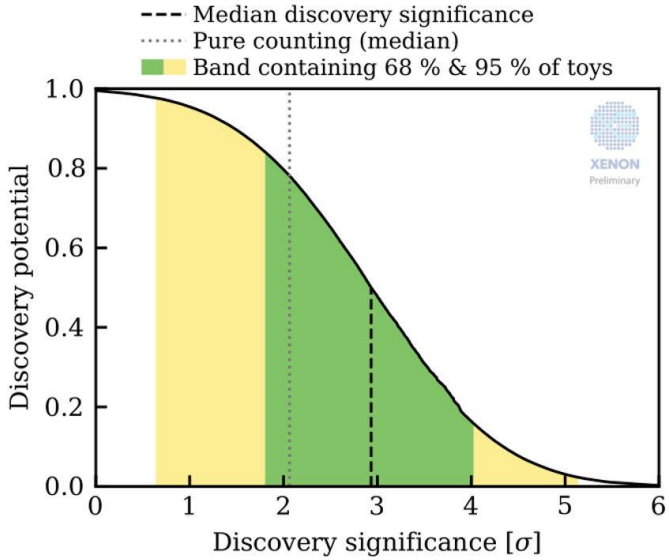
➡ Isolated S1 signals: from pile-up induced single PMT hits, misclassified single electrons,...

➡ Isolated S2 signals: from few-electron pile-up events, notably following high-energy interactions,...



48% to observe > 3σ significance

Component	Expectation	Best-fit
AC (SR0)	7.5 ± 0.7	
AC (SR1)	17.8 ± 1.0	
ER	0.7 ± 0.7	
Neutron	$0.5^{+0.2}_{-0.3}$	
Total background	$26.4^{+1.4}_{-1.3}$	
^{8}B	$11.9^{+4.5}_{-4.2}$	
Observed		



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CEvNS Search – Unblinding

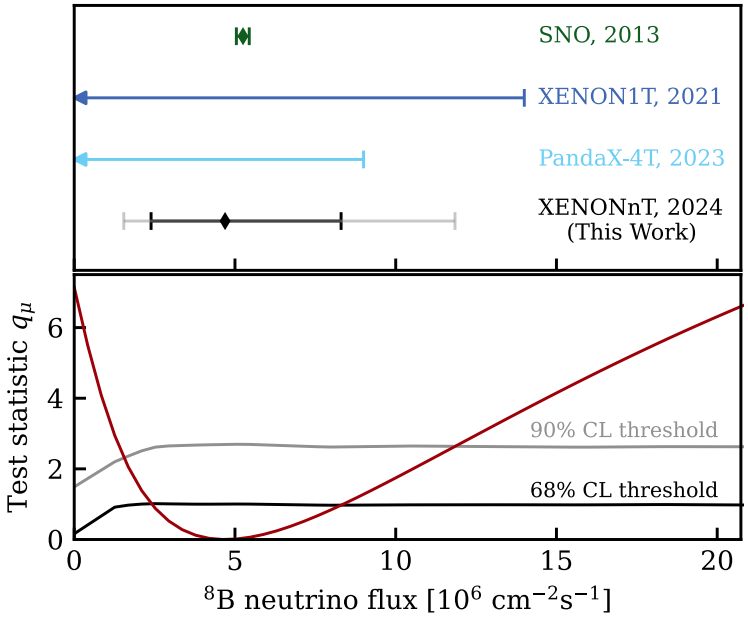
Phys. Rev. Lett. 133, 191002

- Use both science run to perform a blinded analysis, with **316.16 days of livetime** and a fiducial mass of **4.0 (4.1) tonnes in SR0 (SR1)** leading to a **total exposure of 3.51 t x yr**
- Extended binned likelihood in 4D parameter space 3 x 3 x 3 x 3 = 81 bins (cS2, $S2_{prev}/\Delta t_{prev}$, S1 BDT, S2 BDT)

- **^{8}B neutrino flux**: $4.6^{+3.6}_{-2.3} \times 10^6\,cm^{-2}\,s^{-1}$ at 68% C.L. no tension with literature value
- Including constrain from SNO flux → Measure the **flux-weighted CEvNS cross section**: $1.1^{+0.8}_{-0.5} \times 10^{-39}\,cm^2$

-2.3

Component	Expectation	Best-fit
AC (SR0)	7.5 ± 0.7	7.4 ± 0.7
AC (SR1)	17.8 ± 1.0	17.9 ± 1.0
ER	0.7 ± 0.7	$0.5^{+0.7}_{-0.6}$
Neutron	$0.5^{+0.2}_{-0.3}$	0.5 ± 0.3
Total background	$26.4^{+1.4}_{-1.3}$	26.3 ± 1.4
^{8}B	$11.9^{+4.5}_{-4.2}$	$10.7^{+3.7}_{-4.2}$
Observed	37	

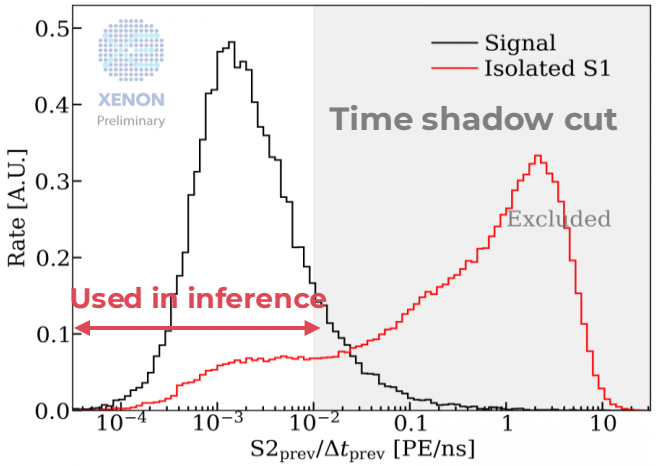


CEvNS Search – Accidental Coincidence

Accidental Coincidence Background

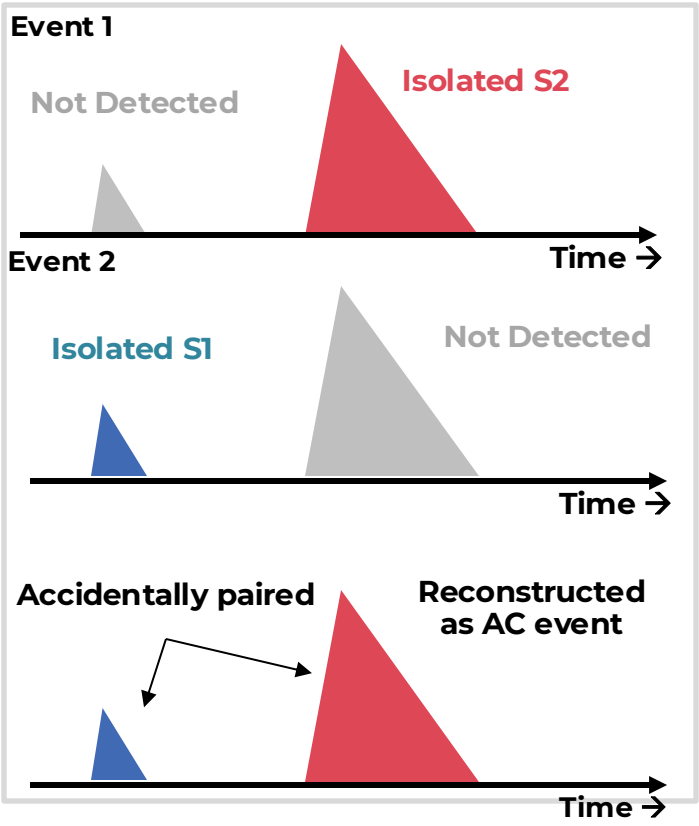
- ACs are accidental pairings of **Isolated S1** and **Isolated S2** signals. Major background near threshold.
- AC rate before mitigation:
  - Isolated S1 rate: ~15 Hz
  - Isolated S2 rate: ~150mHz
  - Raw AC rate: **~400 events/day**

AC Background Mitigation



Iso-peaks believed to be related of high energy events in the TPC.

Mitigated using **analysis cuts** based on time and space information of peaks following a HE peak.



Expected AC Events after Mitigation:

SR0: 7.5 $\pm$ 0.7 | SR1: 17.8 $\pm$ 1.0

WIMP Search – Further tests

After unblinding, further tests performed to identify mismodelling. **No evidence of mismodelling** observed.

Tests for spatial homogeneity in XY: **No evidence of asymmetry in SR1.**